Synchronizer Based on Operational Transformation for P2P Environments

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Abstract

Reconciling divergent copies is a common problem encountered in distributed or mobile systems, asynchronous collaborative groupware, concurrent engineering, software configuration management, version control systems and personal work involving several mobile computing devices. Synchronizers provide a solution by enabling two divergent copies of the same object to be reconciled. Unfortunately, a master copy is generally required before they can be used for reconciling n copies, otherwise copy convergence will not be achieved. This paper presents the principles and algorithm of a Synchronizer which provides the means to reconcile n copies, without discriminating in favour of any particular copy. Copies can be modified (concurrently or not) on different sites and the Synchronizer we propose enables them to be reconciled pairwise, at any time, regardless of the pair, while achieving convergence of all copies. For this purpose, it uses the history of operations executed on each copy and Operational Transformations. It does not require a centralised or ordering (timestamp, state vector, etc.) mechanism. Its main advantage is thus to enable free and lazy propagation of copy updates while ensuring their convergence – it is particularly suitable for P2P environments in which no copy should be favoured.

Keywords

Replication, copy consistency, reconciliation, history merge, synchronizer, operational transformation

1. Introduction

Users involved in mobile computing, concurrent engineering or distributed collaborative work, generally work on copies of shared objects. For instance, in mobile computing a user can replicate an object (calendar, file, address book, etc.) on mobile devices (Laptop, PDA, etc.) before disconnection and then manipulate these copies in disconnected work and on different devices. In asynchronous or multi-synchronous [Do95] collaborative groupware and distributed engineering, each user manages its private copy of the shared object (document, map, etc.) and propagates its updates to the others (or makes them public) when connected. In both cases, as each copy of the same object can be modified separately and independently of the others, copies could diverge and therefore have to be reconciled [SS05].

In this context, a *Synchronizer* is a tool that enables *two copies* of the same object to be reconciled in order to obtain an integrated view of the object. It takes two divergent copies of the object as an input and then returns the copies in the same state, after somehow merging the updates. For this merging, Synchronizers use a mechanism based on the state of copies or on the history and semantic properties of operations executed on these copies.

File Synchronizers (Microsoft's Briefcase, Power Merge, Windows File Synchronizer, Unisson [BP98], etc.) consider the object to be a file hierarchy. They allow create/delete actions on files and directories, and also updates, except when they concern two copies of the same file to be propagated from one copy of the file system to another. Solving the conflict is delegated to the user when updates concern two copies of the same file. Data Synchronizers (Palm Pilot Hotsync, Puma Technology Intellisync, Microsoft ActivSync, Apple I-Sync, etc.) allow reconciling and merging of updates relative to two copies of the same file (calendar, address book, etc.), while delegating to the user conflicting situations which generally correspond to non-commutative actions. Several merge tools [MD94] presently used in the field of collaborative work and also in software engineering can be considered as Data Synchronizers – they allow two copies of the same file to be reconciled in accordance with the data type (text [Be90, Ti85], UML or XML [TKS03]), after having detected divergences using, for instance, Diff algorithms [CG97, MD94]. In another context, a reconciliation platform called IceCube [KRS01], was proposed in order to reconcile divergent copies and to merge (in a combinatory manner) their histories using semantic properties of operations executed on these copies and also using two kinds of constraints, i.e. static (e.g. when concerning non-commutative operations) and dynamic (e.g. when referring to object state). All of these merging and synchronizing tools, which were initially designed for reconciling two copies, can also be used for reconciling n copies (with n > 2), on condition that a master copy exists and that each copy is reconciled with the master copy, otherwise copy convergence will not be achieved.

Synchronizing multiple copies of the same object can be obtained in a synchronous or asynchronous mode. In *synchronous methods*, all the copies play the same role and no copy is favoured. Among these, methods based on Operational Transformations [EG89], and developed for collaborative (CSCW) and real-time environments [RNG96, SYZ97, SCF97, SCF98, SE98, VCF00, SXS04, FVD04] maintain copy consistency of the same object by memorizing operations in histories and exploiting their semantic properties. In these environments, every operation generated by a user is immediately executed on his copy before broadcasting to all the other copies in order to be executed on them. As concurrent operations are not necessarily executed in the same order on each copy, they need to be ordered (by means of timestamps, state vectors or sequencer) and then transformed before being executed using, for instance, Operational Transformation, to achieve copy convergence. These methods used to synchronize n copies are limited because of their synchronous aspect and because some ordering mechanisms (timestamps, state vectors, etc.) must be available. Hence, they are not suitable for P2P environments.

With asynchronous methods, synchronizing multiple copies involves pairwise copy synchronization. To our knowledge, all published methods require a master copy, also called primary or public copy. Every copy therefore must be separately resynchronized with the master copy to achieve copy convergence. Examples of such methods are given by Configuration Management Environments [Be90, CW98, Es00], most of which are based on the *Copy/Modify/Merge* paradigm. Briefly, the master copy of the object is stored in the public space. Two (or several) users can simultaneously work on their private copy of the object, provided it has been *copied* in their private workspace. User U_1 can then *modify* his copy and propagate modifications to the master copy by committing, provided that no user has committed from the time when user U_1 downloaded the object copy into his workspace and the one he wants to commit. If this is not the case, user U_1 needs to synchronize his copy with the last committed version and to download the latter into his workspace before *merging* his modifications with this last committed version using merge tools [MD94]. Version control systems based on these principles were specified to synchronize text files [Be90, Ti85], XML files [TKS03] or graphical objects [IN04, IN04b]. Copies are reconciled using state of their representation [Be90, Ti85, TKS03, IN04] and more recently history and semantic properties of operations [IN04b].

A Synchronizer actually has the same objective as an asynchronous method. From this standpoint, a generic data Synchronizer was proposed in [MSO03] to synchronize updates on n copies (pairwise) using the same master copy. This Synchronizer is built on an adaptation of an algorithm which was initially proposed in the context of distributed real-time collaborative (synchronous) environments [VCF00]. It exploits semantic properties and histories of operations executed on the copies and merges two histories using Operational Transformations [EG89].

The fact that a master copy is required to (pairwise) synchronize updates of n copies of the same object is incompatible with a P2P environment in which no copy should be favoured. Indeed, a P2P environment offers a completely decentralised approach for sharing objects by permitting replication of copies of the same object from site to site. Unfortunately, in existing P2P systems, there is only partial or no copy consistency, i.e. when a copy is updated the modification is not propagated to all the other copies. Although this aspect is not important for musical files, it may be for other applications. In popular P2P systems involving millions of users, i.e. Gnutella and Kazaa, manipulated objects are read-only files, so updates are not taken into account. In Freenet [CMH02], updates are partially taken into account insofar as they are propagated from origin sites to neighbour sites when connected. In P-Grid [ACD03], update propagation is ensured by an algorithm offering probabilistic guarantees for copy consistency. However, the main drawback is that updates on copies of the same object can only come from the origin site of this object, i.e. from a master copy.

In this paper, we present a *Synchronizer* that allows copy consistency, *without discriminating in favour of any particular copy*. Even though the copies may have been modified (concurrently or not) on different sites, the Synchronizer we present, can reconcile them pairwise, regardless of the pair, and copy consistency is always ensured. The main advantage of this Synchronizer is that it allows *free and lazy propagation* of updates originating from the different copies; so, it is particularly suitable for P2P environments in which no copy is favoured. It uses the history of operations executed on each copy and is based on Operational Transformations.

The paper is set up as follows. Section 2 reviews the Synchronizer principle as well as the model, based on synchronous collaborative algorithms and on Operational Transformations, that inspired our proposal. Section 3 presents the algorithm of a Synchronizer, called MOT1, that ensures copy reconciliation while requiring a master copy. Section 4 highlights the limits of MOT1 when no master copy is available. Then we outline the principles and the algorithm of an original Synchronizer, called MOT2, which enables any two copies to be reconciled and therefore any number of copies, without favouring any particular copy, but while ensuring their convergence. Finally, some properties of histories produced by MOT2 are described and MOT2 proof is provided.

2. Objectives and Underlying Model

2.1 Synchronizer Principle

In the following, we consider an object (i.e. text, graphics, file, file system, XML tree, calendar, etc.) can be handled using definite operations {op} and is replicated on different sites. With each copy C of the object, the history H of operations that have been executed on C is associated. Initially, the copies are identical and they correspond to the same object state, then they progress independently of each other on their own site, which causes them to diverge. A Synchronizer (see Figure 1) is able to reconcile two divergent copies of the same object. As an entry, it takes both copies to be reconciled as well as their associated histories, thus producing both identical copies as well as their corresponding histories which have become equivalent. A couple (C, H), where C is the copy and H its associated history, is indicated by the name S of the site that manages the copy C – so we may talk about synchronizing either some copies or some sites. Synchronizing sites S_i and S_j is denoted Synch(S_i, S_j).

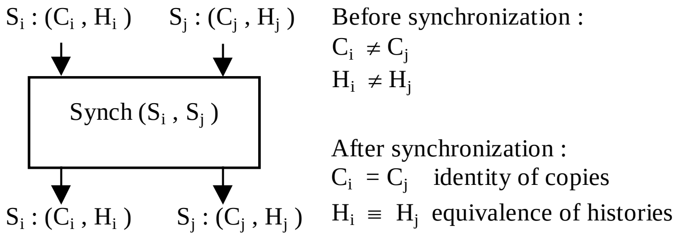


Figure 1. Synchronizer principle

Two kinds of synchronizers are considered. A Synchronizer *with a master site* assumes the existence of a particular site, called the master site, and only permits synchronization between any site and the master site. On the contrary, a Synchronizer *without a master site* permits synchronization between any two sites.

The Synchronizers we present here rely on an algorithm that can merge the histories H_i and H_j associated with copies and obtain two *identical* histories. This algorithm can be either centralised (so it runs on a single site) or distributed (so it runs on two sites, each one managing one copy and the associated history).

The following sections review the different principles underlying this algorithm: copy synchronization using synchronous collaborative algorithms, especially using SOCT4 as well as Operational Transformations.

2.2 Synchronous Collaborative Algorithms and Operational Transformations

Collaborative work often relies on the use of shared objects that are concurrently accessed by different users. In order to conciliate both availability and reactivity constraints when the environment is distributed, objects are generally replicated so that a copy is associated with every site or user. Therefore, the purpose of synchronous collaborative algorithms is to maintain the consistency of these copies in real-time. The real-time aspect means that an operation generated by a user is immediately executed on his copy and *integrated* as soon as possible on the other copies. Copy consistency involves three properties: (1) causality preservation among users' actions, (2) user intention preservation, and (3) copy convergence.

The difference between the various algorithms [EG89, RNG96, SYZ97, SCF97, SCF98, SE98, VCF00] concerns how they achieve *integration* of an operation. From a general standpoint, the history of operations whose execution leads to the current state is required for each object. When an operation op is generated at a site, it is immediately executed on the current state of the copy at this site and appended to the history, then broadcast to the other sites. The reception of an operation op by a site and its integration into the history at this site must take operations which are concurrent to op and already executed on the copy into account in order to determine the operation op' whose execution on the current state of the copy realises the same intention as the operation op. The transformation of op into op' is achieved using transposition functions, forward transposition and backward transposition [SCF97, SE98], called Operational Transformations. However, to guarantee copy convergence, Operational Transformations must meet two conditions called C1 and C2 [EG89, RNG96]. We can distinguish two kinds of collaborative algorithms:

1. algorithms [SCF98, SE98] for which the histories associated with the copies can be different (i.e. concurrent operations may be ordered in different ways according to the sites) while being *equivalent*. These algorithms use both forward transposition and backward transposition and conditions C1 and C2 must be met.
2. algorithms [SYZ97, VCF00] for which the histories associated with the copies are *identical* (i.e. concurrent operations appear in the same order on all the sites). In this class, the SOCT4 algorithm [VCF00] has a twofold advantage. It only uses forward transposition, and secondly condition C2 does not have to be met.

2.3 Forward Transposition

Forward transposition is used when concurrent and non-commutative operations are executed on copies in different orders. To illustrate this concept, let us consider two copies of an object, O_1 and O_2, that are in the same initial state. Let us suppose that operation op_1 [resp. op_2] executed on copy O_1 [resp. O_2] leads to the state $O_1.op_1$ [resp. $O_2.op_2$]. Later, the execution of op_2 [resp. op_1] on copy O_1 [resp. O_2] leads to the state $O_1.op_1.op_2$ [resp. $O_2.op_2.op_1$]. When operations are not commutative[1], the resulting states are not equivalent ($O_1.op_1.op_2 \not\equiv O_2.op_2.op_1$). In these conditions, the forward transposition allows transformation of an operation before its execution so that it takes all concurrent operations serialized before it into account. In short, the forward transposition function, denoted in the following as Transpose-forward(op_1, op_2), is specific to a couple of concurrent operations (op_1, op_2) which are defined from the same object state. As a result, it gives the operation op_2' (also written as $op_2^{op_1}$) which has the same effect as op_2 but which is defined from the state resulting from the execution of op_1, and op_2' is called the forward transposition of op_2 with op_1. To guarantee copy convergence, Operational Transformations and particularly forward transpositions must meet condition C1 [EG89, RNG96] which is summed up by state equivalence: $\forall O_i$, $O_i.op_1.op_2' \equiv O_i.op_2.op_1'$. It generally must meet a further condition C2 which is not detailed.

Example 1. Let us assume that object O is represented as a string of characters and the operation insert(p, c) inserts character c at position p in the string. Copies O_1 and O_2 are in the same initial state

[1] That concerns the "forward" commutativity [We88], as opposed to the "backward" commutativity.

"efect". The operation op_1 = insert(2,'f') executed on copy O_1 adds 'f' at position 2, whereas operation op_2 = insert(6,'s'), which is concurrently executed on copy O_2, adds 's' at the end of the string. Execution of these operations in different orders leads to copies in divergent states: $O_1.op_1.op_2 \equiv$ "effecst" and $O_2.op_2.op_1 \equiv$ "effects". To guarantee copy convergence, operation op_2 [resp. op_1] has to be forward transposed with op_1 [resp. op_2] before being executed on copy O_1 [resp. O_2] so as to take the concurrent operation op_1 [resp. op_2] serialized before it into account, in order to obtain: $O_1.op_1.op_2' \equiv O_2.op_2.op_1' \equiv$ "effects". The transposition function to be used and meeting condition C1 is as follows:

```
Transpose-forward(insert($p_1$, $c_1$), insert($p_2$, $c_2$)) =
        case  $p_1$ ? $p_2$  of
                $p_1 < p_2$ : return  insert($p_2$+1, $c_2$) ;
                $p_1 > p_2$ : return  insert($p_2$ , $c_2$) ;
                $p_1 = p_2$ : if $c_1 = c_2$  then  return  id ;
                        elsif  pr($c_2$) > pr($c_1$) then   return  insert($p_2$ , $c_2$) ;
                        else  return insert($p_2$+1 , $c_2$) ; endif ;
        endcase.
```

The forward transposition of op_2 = insert(6,'s') with op_1 here would be op_2' = Transpose-forward(insert(2,'f'), insert(6,'s')) = insert(7,'s'), whereas the forward transposition of op_1 = insert(2,'f') with op_2 would give the operation $op_1' = op_1$ as a result.

2.4 Relationships between Operations and Histories

By convention, we will say that an operation is executed on a site, when it is executed on the copy located at this site.

Definition 1. The history H_i, associated with the copy C_i at site S_i, memorizes the sequence of operations that transforms the copy C_i from its initial state into its current state, when executed in this order on copy C_i.

More precisely, a history H_i is constituted by elements such as <Id_{op}, S_{op}, op> where op is an operation executed on the copy associated with H_i, S_{op} the site where the operation was generated and Id_{op} the operation identifier. Operations stored in the history H_i at site S_i have been either generated at S_i and therefore immediately executed on S_i, or were generated at another site S_j and executed on S_i as a result of synchronizing S_i with S_j or with another site.

Two operations are related by a causal ordering relation or are concurrent.

Definition 2. Given any two operations op_k and op_l, generated at sites S_{op_k} and S_{op_l} we say that op_k *causally precedes* op_l (noted $op_k \rightarrow_C op_l$) iff: (i) $S_{op_k} = S_{op_l}$ and op_k was generated *before* op_l, or (ii) $S_{op_k} \neq S_{op_l}$ and op_l was generated *after* the execution of op_k by site S_{op_l}, or (iii) there is an operation op_m such that $op_k \rightarrow_C op_m$ and $op_m \rightarrow_C op_l$.

Therefore, any new operation op generated at S_i and executed on the current state of the copy C_i is such that: $\forall op_i \in H_i$, then $op_i \rightarrow_C op$.

Definition 3. Operations op_k and op_l are said to be *independent* or *concurrent* (noted op_k // op_l) iff: not ($op_k \rightarrow_C op_l$) and not ($op_l \rightarrow_C op_k$).

The relation $\rightarrow_C$ expresses the potential causality between the operations. When op_k *causally precedes* op_l, op_l is assumed to be dependent on the effects of op_k. In other words, the generation of op_l takes the effects produced by the execution of op_k into account. Conversely, when op_k and op_l are concurrent, then these operations are completely independent and neither one has been affected by the other.

The order of operations in H_i expresses *precedence*.

Definition 4. Given two operations op_k and op_l in the history H_i, op_k is said to *precede* op_l (noted $op_k \rightarrow_{H_i} op_l$) iff op_k appears *before* op_l in H_i.

Let us note that *precedence* is compatible with the causal ordering relation, i.e. if $op_k \rightarrow_C op_l$ then $op_k \rightarrow_{H_i} op_l$. However, two operations may belong to the same history as a result of a synchronization, without having a causal precedence relation between them.

2.5 Principle of Integration in SOCT4

This section details the integration procedure of SOCT4 [VCF00], which is the basis of our synchronizer proposal. In SOCT4, operations are memorized in the histories associated with the copies according to a global unique order. To this end, a timestamp delivered by a sequencer is associated with each operation, and determines its position in every history. The integration procedure is executed by a site whenever an operation generated and broadcast by a remote site is received (reception is sequential in the timestamp order). It determines the operation to be executed on the current state of the local copy and inserts the received operation into the history at the position corresponding to its timestamp (see Figure 2).

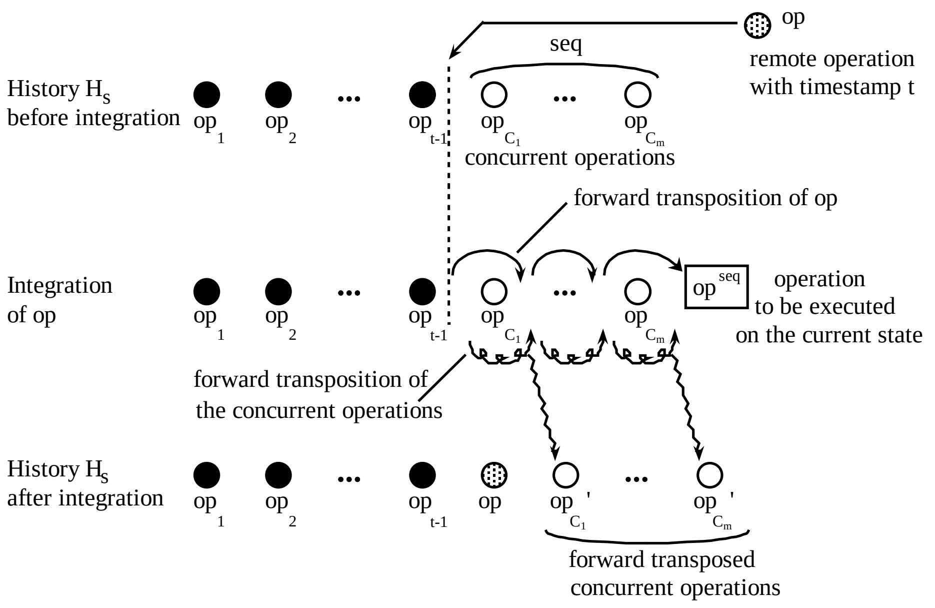

op
remote operation with timestamp t
seq
History H_S before integration
op_1 op_2 op_t-1 op_C1 op_Cm
concurrent operations
forward transposition of op
Integration of op
op^seq
operation to be executed on the current state
forward transposition of the concurrent operations
History H_S after integration
op_1 op_2 op_t-1 op op'_C1 op'_Cm
forward transposed concurrent operations

Figure 2. Integration of an operation in SOCT4

The integration of operation op, with timestamp t, in position t, is based on the assumption that op is defined on the state resulting from the execution of operations op_1 to op_{t-1} and that all operations located from position t (sequence seq) are concurrent to op.

The *Integration* procedure defined below is called to integrate the remote operation op, received as a triplet $<Id_{op}, S_{op}, op>$, in position t in history H_S of site S.

Notations:

C_S : copy of the object on site S
H_S : representation of the history by a table of items in the form $<Id_{op}, S_{op}, op>$;
$H_S[k]$.operation corresponds to the field op of $H_S[k]$
sizeofH_S : number of items in H_S

```
procedure Integration (H_S, t, <Id_op, S_op, op>) ;
    -- Step 1. shift the history to insert <Id_op, S_op, op> in position t
    for k:= sizeofH_S downto t do H_S[k+1]:= H_S[k] ; end for ;
    H_S[t]:= <Id_op, S_op, op> ; sizeof H_S:= sizeofH_S +1 ;
    -- Step 2. determine the operation to be executed on the current
    -- state and transform operations that follow op in H_S
    for k :=t+1 upto sizeofH_S do
            op_k:= H_S[k].operation ;
            $H_S$[k].operation:= Transpose-forward(op, $op_k$) ;
            op:= Transpose-forward($op_k$, op) ;
    end for ;
    -- Step 3. execute the obtained operation on the copy of S
    execute(op, $C_S$) ;
end  Integration ;
```

Step 2 is the essential integration step. Along this step, the operation op is forward transposed with each operation of seq; the resulting operation, noted op^{seq}, is executed on the current state of the copy. During the calculation of op^{seq}, each operation of seq is transposed to take the insertion of op in H_S into account. More precisely, considering seq=$op_{c_1}.op_{c_2}.\dots op_{c_m}$, each operation op_{c_i} of seq is forward transposed with $op^{seq_{i-1}}$, where seq_{i-1}= $op_{c_1}.op_{c_2}.\dots op_{c_{i-1}}$ is the sequence of operations in seq that precede op_{c_i}. So, operation op_{c_i} is replaced in H_S by $op_{c_i}^{op\ seq_{i-1}}$ with op^{seq_0} =op. In the *Integration* procedure, Transpose-forward(op, op_k) is the function that delivers $op_{c_i}^{op^{seq_{i-1}}}$ and Transpose-forward(op_k, op) is the function that delivers op^{seq_i}, assuming that i=k-t.

The memorized history H_S does not correspond to the real history (i.e. the sequence of operations actually executed on the local copy) but it is equivalent to it. The advantage of SOCT4 is that the histories memorized on the different sites converge towards the same history and are finally identical when all operations have been integrated within all sites.

Note that the integration of an operation in the last position in H_S does not require any transposition. It only involves memorizing a new item. For clarity, we introduce the *Append* procedure, which in the following enables us to distinguish the integration with transposition from the integration without transposition.

```
procedure **Append** ($H_S$, <$Id_{op}$, $S_{op}$, op>) ;
    sizeof$H_S$:= sizeof$H_S$ +1 ;
    $H_S$[sizeof$H_S$]:= <$Id_{op}$, $S_{op}$, op> ;
    execute(op, $C_S$) ;
end Append ;
```

The validity conditions of the SOCT4 integration procedure may be expressed independently of timestamps as follows. Given a history H_S = H_C.seq, the integration of operation op into H_S, after H_C and before seq, is correct if conditions (a) and (b) have been met:

(a) : op is defined from the state produced by the execution of operations in H_C;

(b) : $\forall$ op' $\in$ seq, op' is concurrent to op (i.e. not (op $\rightarrow_C$ op') and not (op'$\rightarrow_C$ op)).

The history resulting from the integration of op is H_C.op.seq', where seq' means that seq operations have been forward transposed with op to take the insertion of op into account.

3. Synchronizer with a Master Site

3.1 Principle

A Synchronizer with a master site using Operational Transformation was derived from SOCT4 [MOS03]. The master site, that we designate by R, maintains the master copy as well as the history H_R of the operations applied to it from the initial state to obtain the current state. By construction, the master copy is the most up-to-date copy among all copies of the object. Any site S that wants to resynchronize its copy absolutely must merge its history H_S with the history H_R of the master copy. The following describes the merging principle.

Before the merge, the histories H_R and H_S are identical until index k_S, where k_S corresponds to the last operation of the history obtained from the most recent merge of sites R and S. So we have: $H_S[j] = H_R[j]$, $\forall j : 1 \leq j \leq k_S$. Let us call H_C this common sub-history (common prefix) of H_R and H_S and let us designate by h_R [resp. h_S] the part of H_R [resp. H_S] that follows H_C. So we get:

$$H_R = H_C.h_R \quad \text{and} \quad H_S = H_C.h_S$$

More precisely, h_S corresponds to the sequence of operations generated at S since the last synchronization of S with R and h_R corresponds to the operations generated at R or at another site that was synchronized with R. The h_R operations are concurrent to the h_S operations.

Merging of histories H_R and H_S involves two phases (see Figure 3). Each one is a direct application of SOCT4.

Phase (1): it proceeds on site S and it makes the history H_S progress. It involves importing h_R and integrating it into H_S from position k_S +1. The obtained history is: $H_S = H_C.h_R.h_S'$ where h_S' is the sub-history h_S modified by forward-transposition to take h_R operations into account.

Phase (2): it proceeds on site R and makes the history H_R progress. It involves importing h_S' and appending (integrating without transposition) it to H_R so as to finally obtain $H_R.h_S'$.

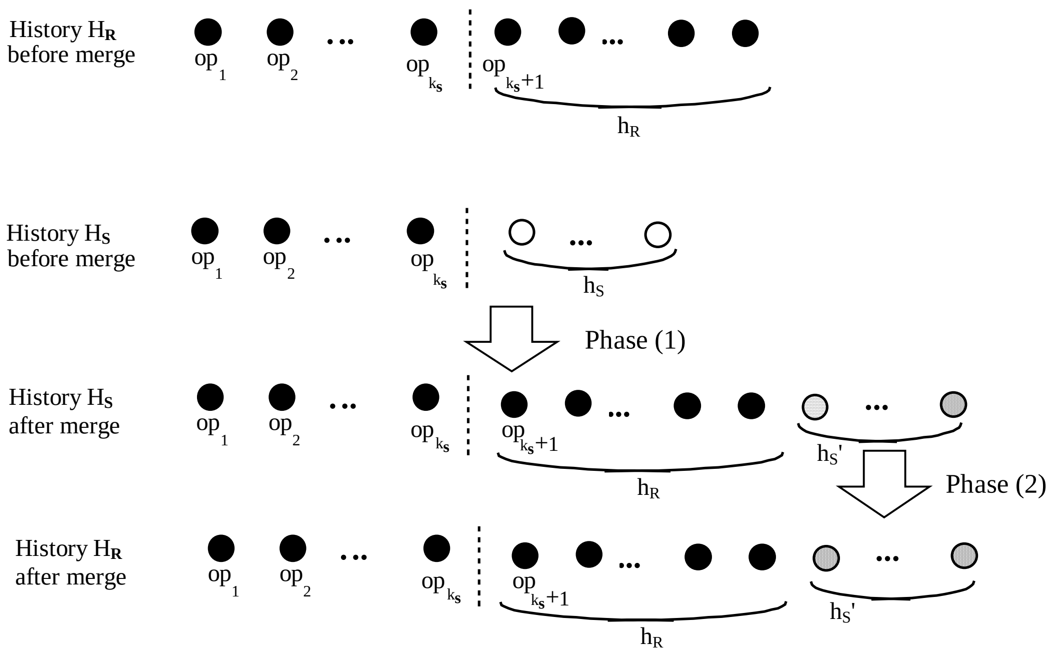

History H_R before merge
op_1 op_2 ... op_{k_S} op_{k_S+1}
h_R
History H_S before merge
op_1 op_2 ... op_{k_S}
h_S
Phase (1)
History H_S after merge
op_1 op_2 ... op_{k_S} op_{k_S+1}
h_R
h_S'
Phase (2)
History H_R after merge
op_1 op_2 ... op_{k_S} op_{k_S+1}
h_R
h_S'

Figure 3. Merging of histories H_S and H_R

In the history resulting from the synchronization of H_R and H_S, note that the sub-history h_R derived from the master site stayed unchanged whereas the sub-history h_S generated at site S was forward transposed with h_R. In fact, every operation present in H_R before the merge is already in a definitive form (shown in black in the figure), and after the merge it remains in the same range in history H_S. The h_S' operations integrated at the end of H_R are also in a definitive form after the merge.

3.2 The MOT1 Algorithm

The principle of the Synchronizer with a master site described above is fulfilled by the history merging algorithm MOT1 ("Merge based on Operational Transformation"). MOT1 here corresponds to a centralized algorithm, and it accepts both couples (C_R, H_R) and (C_S, H_S) as inputs and reconciles the copies C_R and C_S by merging the histories H_R and H_S. As output, it produces both couples (C_R, H_R) and (C_S, H_S), which are identical. To illustrate the fact that MOT1 is above all an history merging algorithm, we voluntarily overlooked copies that are only accessed in the *Integration* and *Append* procedures.

```
procedure MOT1 ($H_R$ , $H_S$) ;
        -- Look for the prefix common to $H_R$ and $H_S$: determine the index $k_S$ reached after the most recent
        -- merging of sites R and S
        k := $k_S$ + 1 ;
        while  k ≤ sizeof$H_R$  loop                              -- Phase (1): integrate $h_R$ into $H_S$
              < $Id_{op}$, $S_{op}$ , op > :=  $H_R$[k] ;
```

```
            Integration ($H_S$, k, < $Id_{op}$, $S_{op}$ , op >) ;              -- $H_R[k] \rightarrow H_S[k]$
            k := k + 1 ;
        endloop ;
        while  k ≤ sizeof$H_S$  loop                                   -- Phase (2): append $h_S$' to $H_R$
            < $Id_{op}$, $S_{op}$ , op > :=  $H_S[k]$ ;
            Append ($H_R$, < $Id_{op}$, $S_{op}$ , op >) ;                      -- $H_S[k] \rightarrow H_R[k]$
            k := k + 1 ;
        endloop ;
    end MOT1 ;
```

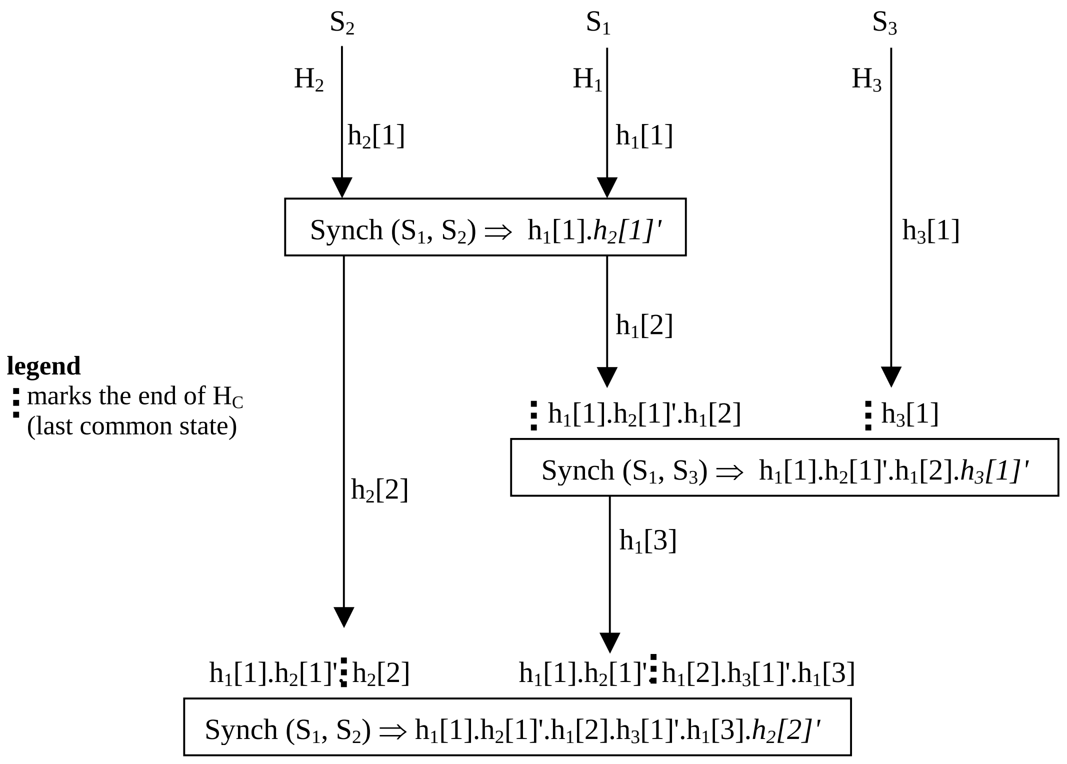
The history resulting from phase (1) is the final history. Phase (2) only expresses the necessary evolution of H_R from its initial state. So, the processing to be performed on the history of each site is emphasized, thus making the distribution of MOT1 on both sites easier.

We observe that phases (1) and (2) in MOT1 are not symmetrical. When distributing the MOT1 algorithm, phase (1) corresponds to the processing to be performed on site S, whereas phase (2) corresponds to the processing to be performed on site R. So, with MOT1, the roles of sites R and S can be considered as not symmetrical during the synchronization. Moreover, their roles are fixed *once and for all* in-so-far as the master site stays the same for all synchronizations.

The proof of MOT1 is given in Appendix A1. Beyond the fact that it is presented as a centralized algorithm, MOT1 differs from [MOS03] by the fact that no sequencer is used. A sequencer is needed in SOCT4 to timestamp and thus to globally order operations broadcast by the various sites. In [MOS03], operation time-stamping enables the master site to control concurrent synchronizations. In MOT1, timestamping is unneces-sary as the merge procedure is executed in a critical section. The operation order naturally corresponds to the order of their integration into the master site history H_R.

Example 2 illustrates a succession of synchronizations of sites S_2 and S_3 with the master site S_1, by using MOT1. The following notations are used. Synch(S_i, S_j) means synchronization of sites S_i and S_j, where S_i is the master site; Synch(S_i, S_j) $\Rightarrow$ introduces the history resulting from synchronization of S_i and S_j. The sequence of operations generated at site S_i between its (n-1)th and nth synchronization is designated by $h_i[n]$; $h_i[n]'$ means that operations in $h_i[n]$ have been forward transposed during the synchronization of S_i with another site (merging $h_i[n]$ with another history).

> *Example 2*. Initially, all copies of the object are in the same state; then sites progress independently from each other (see Figure 4). The history resulting from the first synchronization between S_2 and S_1 is: Synch(S_1, S_2) $\Rightarrow$ $h_1[1].\mathit{h_2[1]'}$ (italics are used to highlight sequences of operations that have been modified by transposition during the synchronization). Then S_2 and S_1 continue to progress independ-ently. Further synchronization of S_3 and S_1 leads to the resulting history: Synch(S_1, S_3) $\Rightarrow$ $h_1[1].h_2[1]'.h_1[2].\mathit{h_3[1]'}$, where $h_3[1]$ has been forward transposed with the master site history. Just be-fore resynchronizing S_2 and the master site S_1, the respective histories of S_2 and S_1 are :
>
> $$H_2 = h_1[1].h_2[1]'.h_2[2] \quad \text{and} \quad H_1 = h_1[1].h_2[1]'.h_1[2].h_3[1]'.h_1[3].$$
>
> Synchronizing S_1 and S_2 leads to the result: Synch(S_1, S_2)$\Rightarrow$ $h_1[1].h_2[1]'.h_1[2].h_3[1]'.h_1[3].\mathit{h_2[2]'}$.
>
> All copies converge towards the *same* state and will be identical when, in the absence of newly gener-ated operations, all sites get resynchronized with the master site S_1 (after S_3 has been resynchronized with S_1, in the absence of new operations generated by S_2, S_3 and S_1).



S_2
S_1
S_3
H_2
H_1
H_3
$h_2[1]$
$h_1[1]$
Synch (S_1, S_2) ⇒ $h_1[1].\mathit{h_2[1]'}$
$h_3[1]$
$h_1[2]$
legend
⋮ marks the end of H_C (last common state)
⋮ $h_1[1].h_2[1]'.h_1[2]$
⋮ $h_3[1]$
$h_2[2]$
Synch (S_1, S_3) ⇒ $h_1[1].h_2[1]'.h_1[2].\mathit{h_3[1]'}$
$h_1[3]$
$h_1[1].h_2[1]'$⋮$h_2[2]$
$h_1[1].h_2[1]'$⋮$h_1[2].h_3[1]'.h_1[3]$
Synch (S_1, S_2) ⇒ $h_1[1].h_2[1]'.h_1[2].h_3[1]'.h_1[3].\mathit{h_2[2]'}$

Figure 4. An example of synchronization by MOT1 with the master site S_1

In summary, the following features can be retained for MOT1.

Input histories: $H_R = H_C.h_R$
and $H_S = H_C.h_S$
where h_S is a sequence of operations generated at site S and
h_R is a sequence of operations generated at other sites than S.
Resulting history: Synch(R, S) ⇒ $H_C.h_R.h_S'$
where h_S' means that operations of sub-history h_S have been forward transposed with respect to h_R operations.

4. Synchronizer without a Master Site

4.1 Limitations of MOT1

The principle of a Synchronizer without a master site assumes that sites get synchronized and merge their histories, in pairs, *regardless of the pair associations*, while finally ensuring *copy convergence*. To be able to use the MOT1 algorithm to achieve this, it is necessary to define the role of each S_i and S_j site, before each synchronization Synch(S_i, S_j), since this role is not symmetrical. The role assigned to a site is temporary and only set for the duration of the synchronization. We will provide examples to illustrate the effect on the form of the resulting history and demonstrate the impossibility of obtaining copy convergence.

As a convention in the following, the notation Synch(S_i, S_j) means that when synchronizing sites S_i and S_j, the first S_i site serves as the master site (R).

4.1.1 Arbitrary role assignment to sites

In this section, we assume that each time two sites get synchronized, the site that serves as the master site is chosen arbitrarily.

Example 3. Let us consider sites S_1, S_2 and S_3 whose copies are initially identical and which progress independently (see Figure 5). When assigning the role of master site to the S_1 site, the history resulting from synchronizing S_1 and S_2 is: Synch(S_1, S_2) $\Rightarrow$ $h_1[1].\mathit{h_2[1]'}$. Note that if the role assigned to sites were different, the history resulting from their synchronization would be different: Synch(S_2, S_1) $\Rightarrow$ $h_2[1].\mathit{h_1[1]'}$. Further synchronization of sites S_3 and S_1 results in the following history: Synch(S_3, S_1) $\Rightarrow$ $h_3[1].\mathit{h_1[1]'.h_2[1]''.h_1[2]'}$. As in Example 2, the first two synchronizations are made with S_1. However S_1 plays the role of master site in the first synchronization but not in the second. The histories produced are then different. As no master site is required, it is now possible to directly synchronize S_2 and S_3. Before synchronization we have:

$$H_2 = \mathbf{h_1[1].h_2[1]'}.h_2[2] \qquad \text{and} \qquad H_3 = h_3[1].\mathbf{h_1[1]'.h_2[1]''}.h_1[2]'$$

Note that H_2 and H_3 have no common prefix. Their last common state is the initial state. However, some operations are present in both histories although they appear under *different forms* because they have been transposed; the sequences $h_1[1].h_2[1]'$ in H_2 and $h_1[1]'.h_2[1]''$ in H_3 (shown in bold) exemplify this; they involve operations with the same identity (field <Id_{op}> is identical), but under different forms (field <op> is different). In these conditions, it is no longer possible to synchronize S_3 and S_2 (by either Synch(S_3, S_2) or Synch(S_2, S_3)) when using MOT1 since the input histories do not fulfil the required property (common prefix H_C). Applying the MOT1 merge algorithm would result in a history in which some operations (operations of $h_1[1].h_2[1]'$ and $h_1[1]'.h_2[1]''$) would each appear twice – which of course is incoherent.

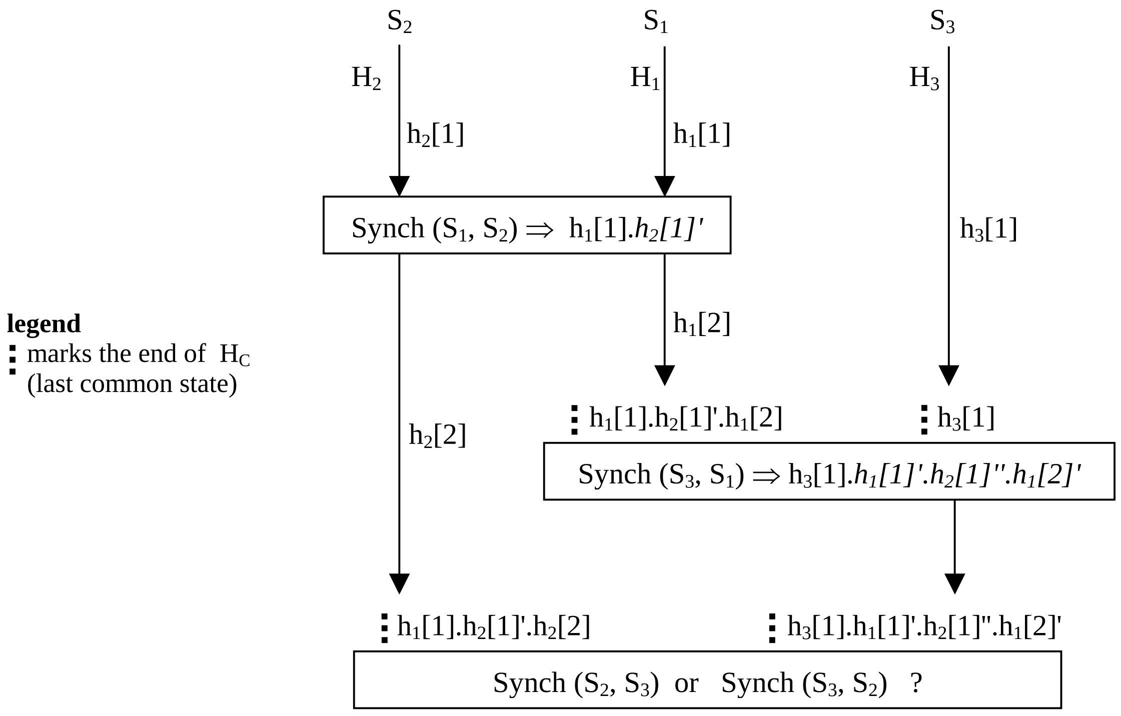

S2
S1
S3
H2
H1
H3
h2[1]
h1[1]
Synch (S1, S2) ⇒ h1[1].h2[1]'
h3[1]
legend
⁝ marks the end of HC (last common state)
h1[2]
h2[2]
⁝ h1[1].h2[1]'.h1[2]
⁝ h3[1]
Synch (S3, S1) ⇒ h3[1].h1[1]'.h2[1]''.h1[2]'
⁝ h1[1].h2[1]'.h2[2]
⁝ h3[1].h1[1]'.h2[1]''.h1[2]'
Synch (S2, S3) or Synch (S3, S2) ?

Figure 5. Synchronizing attempt using MOT1 without a master site

In the following, sequences consisting of operations that are identical in their identity (<Id_{op}>) but different in their form (<op>) and that appear in the same order are called *avatars*. In Example 3, sequences $h_1[1].h_2[1]'$ in H_2 and $h_1[1]'.h_2[1]''$ in H_3 are avatars. Note that avatars are characterized by the fact that they are not defined from the same state in both histories.

4.1.2 Role assignment depending on a predetermined site order

To assign their role to sites that achieve synchronization, we use a predetermined total order between sites. When a synchronization Synch(S_i, S_j) between two sites S_i and S_j occurs, the S_i site serving as the master site is such that $S_i < S_j$. It could be thought that by totally ordering the synchronizing sites, common operations would be defined from the same state in histories to merge. The following example shows that is not the case.

Example 4. Let us consider the four sites S_1, S_2, S_3 and S_4 represented in Figure 6. The order used is: $S_1 < S_2 < S_3 < S_4$. With this convention, the following histories result from successive synchronizations:

Synch(S_1, S_3) $\Rightarrow$ $h_1[1]$;

Synch(S_2, S_4) $\Rightarrow$ $h_2[1]$;

Synch(S_2, S_3) $\Rightarrow$ $\mathbf{h_2[1]}.h_2[2].\boldsymbol{h_1[1]'}.h_3[2]'$;

Synch(S_1, S_4) $\Rightarrow$ $\mathbf{h_1[1]}.\boldsymbol{h_2[1]'}.h_4[2]'$.

Again it can be noted that histories H_1 and H_3 have no common prefix and contain avatars (shown in bold), i.e. some operations are present in both histories (field <Id_{op}> is identical), while they appear under *different forms* (field <op> is different) because they are not defined from the same state. Moreover, it can be noted that the avatars of $h_1[1]$ and $h_2[1]$ appear in *different orders* in each history. Consequently, it is not possible, for the same reasons as previously outlined, to synchronize S_3 and S_1 (by either Synch(S_3, S_1) or Synch(S_1, S_3)) when using MOT1 – applying this merge algorithm would make each avatar of $h_1[1]$ and $h_2[1]$ appear twice in the resulting history.

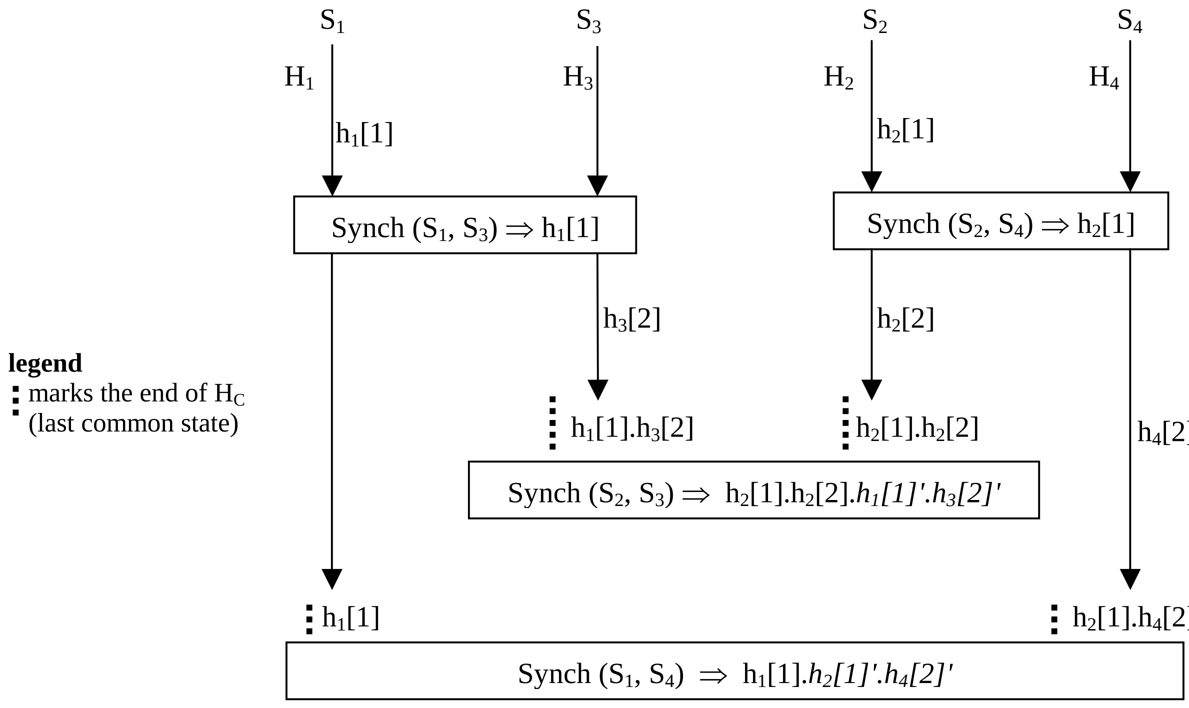


Figure 6. Using MOT1 with a predetermined order between synchronizing sites

To sum up, the use of MOT1 to synchronize a pair of any sites, without favouring any one, is useless since various problems due to characteristics of the produced histories have not finally been solved, namely: (i) the impossibility of guaranteeing the existence of a common prefix in histories that have common sub-histories, (ii) the presence of avatars, and (iii) the possibility for avatars common to several histories to appear in different orders.

4.2 General Principle of MOT2

In the absence of a master site, the MOT2 merge algorithm presented in the following ensures copy convergence while permitting any pair of copies to be synchronized. To obtain this property, MOT2 merges the histories by using *an order between the sites that generate* the operations instead of using an order between the sites that achieve synchronization. A unique global order can thus be built without requiring a centralizing or ordering mechanism (timestamp, state vector, sequencer, etc.). As a result, histories produced by MOT2 are such that the common sub-histories appear in the *same order*. Moreover, in MOT2, the role of sites is totally *symmetrical* when synchronizing. In particular, the history produced by Synch(S_i, S_j) is identical to that produced by Synch(S_j, S_i) (i.e. Synch(S_i, S_j) $\Rightarrow$ identical to Synch(S_j, S_i) $\Rightarrow$).

The basic principle of MOT2 is as follows. Given the input histories: $H_i = H_C.op_i$ and $H_j = H_C.op_j$ where op_i and op_j are operations generated by sites S_{op_i} and S_{op_j}, respectively, the resulting history when synchronizing S_i and S_j is:

if $S_{op_i} < S_{op_j}$ then Synch(S_i, S_j) $\Rightarrow$ $H_C.op_i.\mathit{op_j}'$
if $S_{op_i} > S_{op_j}$ then Synch(S_i, S_j) $\Rightarrow$ $H_C.op_j.\mathit{op_i}'$

where $\mathit{op_i}'$ [resp. $\mathit{op_j}'$] means that operation op_i [resp. op_j] has been forward transposed with operation op_j [resp. op_i].

More generally, given the input histories: $H_i = H_C.op_i.seq_i$ and $H_j = H_C.op_j.seq_j$ where op_i and op_j are operations respectively generated by sites S_{op_i} and S_{op_j}, seq_i and seq_j are sequences of operations generated by any sites, the choice of the operation (op_i or op_j) to integrate after H_C depends on the generator sites and involves the following effects:

if $S_{op_i} < S_{op_j}$ then integration of op_i in H_j, which gives:
$H_i = H_C.op_i.seq_i$ (H_i unchanged) and $H_j = H_C.op_i.\mathit{op_j}'.\mathit{seq_j}'$
if $S_{op_i} > S_{op_j}$ then integration of op_j in H_i, which gives:
$H_i = H_C.op_j.\mathit{op_i}'.\mathit{seq_i}'$ and $H_j = H_C.op_j.seq_j$ (H_j unchanged)

where $\mathit{op_i}'.\mathit{seq_i}'$ [resp. $\mathit{op_j}'.\mathit{seq_j}'$] means that operations $op_i.seq_i$ [resp. $op_j.seq_j$] have been forward transposed with the operation op_j [resp. op_i].

The following example illustrates the application of this principle in the execution of Example 4.

Example 5. As in Example 4, we have: Synch(S_1, S_3) $\Rightarrow$ $h_1[1]$ and Synch(S_2, S_4) $\Rightarrow$ $h_2[1]$. We will now detail the next two synchronizations Synch(S_2, S_3) and Synch(S_1, S_4) when using MOT2. We recall that the order of the sites is: $S_1 < S_2 < S_3 < S_4$.

1. Detail of Synch(S_2, S_3). Before synchronization, the histories of sites S_2 and S_3 are: $H_2 = h_2[1].h_2[2]$ and $H_3 = h_1[1].h_3[2]$. Note that H_C is empty. Synchronizing S_2 and S_3 according to MOT2 successively achieves the following.

a. Integrate operations of $h_1[1]$ into H_2 as S_1, generator site of $h_1[1]$, and S_2, generator site of $h_2[1]$, are such that $S_1 < S_2$. The result is:

$H_2 = \underline{h_1[1]}.\mathit{h_2[1]'}.\mathit{h_2[2]'}$ and $H_3 = \underline{h_1[1]}.h_3[2]$.

(We underline the resulting common sub-history and write the operations modified by forward transposition in italics).

b. Integrate operations of $h_2[1]'$ into H_3 as S_2, generator site of $h_2[1]'$, and S_3, generator site of $h_3[2]$, are such that $S_2 < S_3$. The result is:

$H_2 = \underline{h_1[1].h_2[1]'}.h_2[2]'$ and $H_3 = \underline{h_1[1].h_2[1]'}.\mathit{h_3[2]'}$.

c. Integrate operations of $h_2[2]'$ into H_3 as S_2, generator site of $h_2[2]'$, and S_3, generator site of $h_3[2]'$, are such that $S_2 < S_3$. The result is:

$H_2 = \underline{h_1[1].h_2[1]'.h_2[2]'}$ and $H_3 = \underline{h_1[1].h_2[1]'.h_2[2]'}.\mathit{h_3[2]''}$.

d. Append (integrate without transposition) operations of $h_3[2]''$ into H_2 as the end of H_2 has been reached. The final result is:

$H_2 = H_3 = h_1[1].h_2[1]'.h_2[2]'.h_3[2]''$.

2. Detail of Synch(S_1, S_4). Before synchronization, the histories of sites S_1 and S_4 are: $H_1 = h_1[1]$ and $H_4 = h_2[1].h_4[2]$. Synchronizing according to MOT2 achieves the following.

a. Integrate operations of $h_1[1]$ into H_4 as $S_1 < S_2$. The result is:

$H_1 = \underline{h_1[1]}$ and $H_4 = \underline{h_1[1]}.h_2[1]'.h_4[2]'$.

b. Append (integrate without transposition) operations of $h_2[1]'$ and $h_4[2]'$ into H_1 as the end of H_1 has been reached. The final result is:

$H_1 = H_4 = h_1[1].h_2[1]'.h_4[2]'$.

After these synchronizations it should be pointed out that operations common to histories H_1, H_2, H_3 and H_4 (i.e. $h_1[1].h_2[1]'$) appear in the sa*me* order and constitute their common prefix.

In Example 5, the application of MOT2 produced histories that have common contiguous sequences of operations corresponding to their common prefix. We will see later that this may produce histories that have common non-contiguous sequences of operations, and we will note that these common sequences appear in all histories in the *same* order.

4.3 The MOT2 Merge Algorithm

The principle described in the previous section is achieved by the MOT2 history merging algorithm. MOT2 accepts any two couples (C_i, H_i) and (C_j, H_j) as inputs and reconciles copies C_i and C_j by merging histories H_i and H_j. As an output, both couples (C_i, H_i) and (C_j, H_j) are identical. As for MOT1, we voluntarily over-looked copies only accessed in the *Integration* and *Append* procedures.

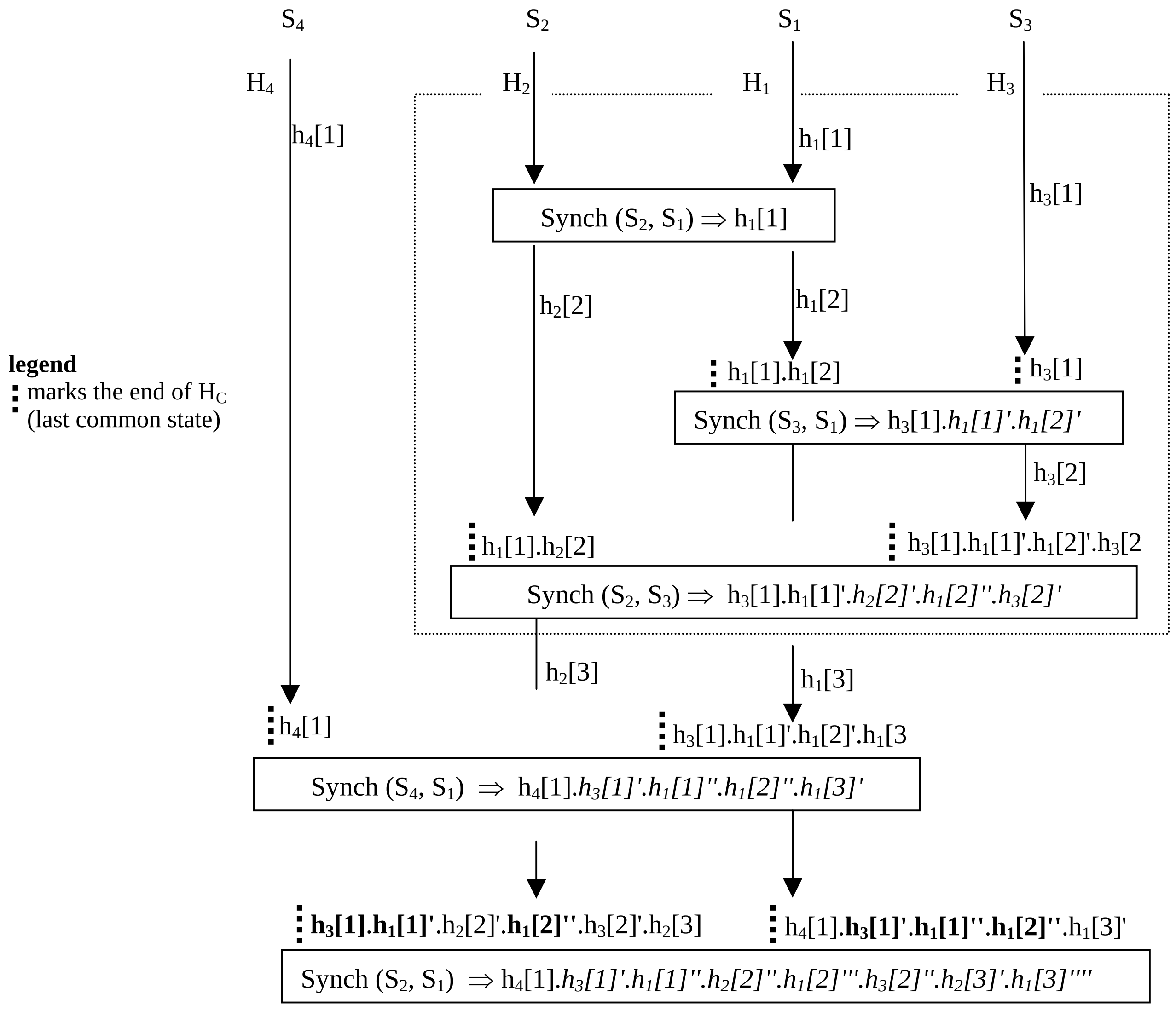
```
procedure MOT2 ($H_i$ , $H_j$) ;
   -- Look for the prefix $H_C$ common to $H_i$ and $H_j$: determine the index $k_S$ of the last operation of $H_C$
   k := $k_S$ + 1 ;
   while ($k \le sizeofH_i$) and ($k \le sizeofH_j$) loop
      < $Id_{op_i}$ , $S_{op_i}$ , $op_i$ > := $H_i[k]$ ;
      < $Id_{op_j}$ , $S_{op_j}$ , $op_j$ > := $H_j[k]$ ;
      case $S_{op_i}$ ? $S_{op_j}$ of
      $S_{op_i} < S_{op_j}$ : Integration ($H_j$ , k, < $Id_{op_i}$ , $S_{op_i}$ , $op_i$ >) ;        -- Integrate $op_i$ into $H_j$
      $S_{op_j} < S_{op_i}$ : Integration ($H_i$, k, < $Id_{op_j}$ , $S_{op_j}$ , $op_j$ >) ;        --Integrate $op_j$ into $H_i$
      $S_{op_j} = S_{op_i}$ : ;                                                -- Operation is present in $H_i$ and $H_j$
      endcase ;
      k := k + 1 ;
   endloop ;                                   -- The end of $H_i$ or $H_j$ has been reached
   while $k \le sizeofH_j$ loop                      -- End of history $H_i$: append the remainder of $H_j$ to $H_i$
      < $Id_{op_j}$ , $S_{op_j}$, $op_j$ > := $H_j[k]$ ;
      Append ($H_i$, < $Id_{op_j}$, $S_{op_j}$, $op_j$ >) ;
      k := k + 1 ;
   endloop ;
   while $k \le sizeofH_i$ loop                      -- End of history $H_j$: append the remainder of $H_i$ to $H_j$
      < $Id_{op_i}$ , $S_{op_i}$ , $op_i$ > := $H_i[k]$ ;
      Append ($H_j$ , < $Id_{op_i}$, $S_{op_i}$ , $op_i$ >) ;
      k := k + 1 ;
   endloop ;
end MOT2 ;
```

MOT2 begins by determining the prefix common to H_i and H_j. Then, the generator sites of operations that follow the common prefix in H_i and H_j are compared in order to determine the operation to be integrated. After integration, the common prefix is augmented by one operation and the process is repeated until the end of one of the histories. The remaining operations of the history which is not terminated are then appended to the other history. When the compared operations op_i and op_j are such that $S_{op_i} = S_{op_j}$, they have the same generator site and are therefore identical (i.e. $Id_{op_i} = Id_{op_j}$ and $op_i = op_j$), which means that the operation is common to both histories H_i and H_j. Therefore, one directly skips to integrate the next operation. MOT2 can thus be applied to two histories that are defined from the same initial state, without explicitly providing their last common state, which will be automatically determined by the algorithm.

The following example illustrates processing of the algorithm and presents a situation where histories produced by MOT2 have common non-contiguous operation sequences.

> *Example 6*. Let us again consider the execution of Example 3 (see Figure 5) completed by adding the S_4 site. Figure 5 slightly modified ($h_2[1]$ is empty and $h_3[2]$ has been added) is visible inside the dotted frame in Figure 7. The site order is: $S_4 < S_3 < S_2 < S_1$.
>
> The histories produced by the MOT2 algorithm after successive synchronizations are now given below.
>
> Synch $(S_2, S_1) \Rightarrow h_1[1]$
>
> Synch $(S_3, S_1) \Rightarrow h_3[1].\mathit{h_1[1]'.h_1[2]'}$
>
> Synch $(S_2, S_3) \Rightarrow h_3[1].h_1[1]'.\mathit{h_2[2]'.h_1[2]''.h_3[2]'}$
>
> Synch $(S_4, S_1) \Rightarrow h_4[1].\mathit{h_3[1]'.h_1[1]''.h_1[2]''.h_1[3]'}$
>
> Note that the impossibility of achieving Synch (S_2, S_3) using MOT1 (see Example 3) is overcome by using MOT2. Before once more synchronizing sites S_2 and S_1, their histories are as follows:
>
> $H_1 = h_4[1].\mathbf{h_3[1]'.h_1[1]''.h_1[2]''}.h_1[3]'$ and $H_2 = \mathbf{h_3[1].h_1[1]'.}h_2[2]'.\mathbf{h_1[2]''}.h_3[2]'.h_2[3]$
>
> Note that H_2 and H_1 contain several avatars (shown in bold), and these appear in the same order. Synchronizing S_2 and S_1 using MOT2 successively achieves the following statements.
>
> a. Integrate $h_4[1]$ into H_2, which gives:
>
> $H_1 = \underline{h_4[1].h_3[1]'.h_1[1]''}.h_1[2]''.h_1[3]'$ (unchanged) and
>
> $H_2 = \underline{h_4[1].h_3[1]'.h_1[1]''}.h_2[2]''.h_1[2]'''.h_3[2]''.h_2[3]'$;
>
> b. Integrate $h_2[2]''$ into H_1, which gives:
>
> $H_1 = \underline{h_4[1].h_3[1]'.h_1[1]''.h_2[2]''.h_1[2]'''}.h_1[3]''$ and
>
> $H_2 = \underline{h_4[1].h_3[1]'.h_1[1]''.h_2[2]''.h_1[2]}'''.h_3[2]''.h_2[3]'$ (unchanged);
>
> c. Integrate $h_3[2]''$ into H_1, which gives:
>
> $H_1 = \underline{h_4[1].h_3[1]'.h_1[1]''.h_2[2]''.h_1[2]'''.h_3[2]''}.h_1[3]'''$ and
>
> $H_2 = \underline{h_4[1].h_3[1]'.h_1[1]''.h_2[2]''.h_1[2]'''.h_3[2]''}.h_2[3]'$ (unchanged);
>
> d. Integrate $h_2[3]'$ into H_1, which gives:
>
> $H_1 = \underline{h_4[1].h_3[1]'.h_1[1]''.h_2[2]''.h_1[2]'''.h_3[2]''.h_2[3]'}.h_1[3]''''$ and
>
> $H_2 = \underline{h_4[1].h_3[1]'.h_1[1]''.h_2[2]''.h_1[2]'''.h_3[2]''.h_2[3]'}$ (unchanged);
>
> e. Append $h_1[3]''''$ into H_2, which gives:
>
> $H_1 = H_2 = h_4[1].h_3[1]'.h_1[1]''.h_2[2]''.h_1[2]'''.h_3[2]''.h_2[3]'.h_1[3]''''$;
>
> Finally we get: Synch $(S_2, S_1) \Rightarrow h_4[1].\mathit{h_3[1]'.h_1[1]''.h_2[2]''.h_1[2]'''.h_3[2]''.h_2[3]'.h_1[3]''''}$.

In Example 6, we observe that the common sequences of operations, either contiguous or not, appear in the *same order* in all histories. This is actually the main feature of MOT2. While allowing free propagation of histories, since a site may at any time synchronize its copy with any site, MOT2 guarantees that sub-histories common to various histories appear in the *same order* (see Theorem 5). By means of successive synchronizations, a *global order* is built without requiring any centralized mechanism. MOT2 thus guarantees that copies will converge towards the same state. For this reason, MOT2 is particularly well suited to P2P environments where copies may be concurrently modified without discriminating in favour of any copy or site. As MOT2 uses Operational Transformations (i.e. forward transposition) and SOCT4 to merge histories, it achieves automatic copy reconciliation while respecting causality precedence between operations when this exists.



S4
S2
S1
S3
H4
H2
H1
H3
h4[1]
h1[1]
h3[1]
Synch (S2, S1) ⇒ h1[1]
h2[2]
h1[2]
legend
marks the end of HC
(last common state)
h1[1].h1[2]
h3[1]
Synch (S3, S1) ⇒ h3[1].h1[1]'.h1[2]'
h3[2]
h1[1].h2[2]
h3[1].h1[1]'.h1[2]'.h3[2
Synch (S2, S3) ⇒ h3[1].h1[1]'.h2[2]'.h1[2]''.h3[2]'
h2[3]
h1[3]
h4[1]
h3[1].h1[1]'.h1[2]'.h1[3
Synch (S4, S1) ⇒ h4[1].h3[1]'.h1[1]''.h1[2]''.h1[3]'
h3[1].h1[1]'.h2[2]'.h1[2]''.h3[2]'.h2[3]
h4[1].h3[1]'.h1[1]''.h1[2]''.h1[3]'
Synch (S2, S1) ⇒ h4[1].h3[1]'.h1[1]''.h2[2]''.h1[2]'''.h3[2]''.h2[3]'.h1[3]''''

Figure 7. Example of synchronization using MOT2

4.4 MOT2 Properties and Proof

This section presents the properties and theorems that enable us to prove the correction of the MOT2 merge algorithm. Demonstrations of the theorems are given in the Appendix.

The subsequent results we are interested in concern the operation order. Consequently, although the operations may appear under different forms because of the transpositions, we will combine the operation and its various transposed forms in the notation. In other words, the notation op_k will represent either the generated operation op_k or its forward transposed forms op_k', op_k'', etc. The fact that an operation got transformed through transpositions therefore no longer appears in the formulations.

Property P1. Given H_i, $\forall op_k$ and $\forall op_l \in H_i$ such that: $op_k \rightarrow_{H_i} op_l$, after merging H_i with another history using MOT2, the precedence in the resulting history H is still: $op_k \rightarrow_H op_l$.

As (see Definition 4) the precedence is compatible with the causal ordering relation, merging preserves both the precedence ($\rightarrow_H$) and the causal precedence relation ($\rightarrow_C$).

Let us now consider the histories H_i and H_j of sites S_i and S_j with a common prefix H_C. Let us call op_i and op_j the operations belonging to histories H_i and H_j, respectively, and defined from the sa*me* state (the state left by H_C). Then we have: $H_i = H_C.op_i.seq_i$ and $H_j = H_C.op_j.seq_j$, where seq_i and seq_j are sequences of any operations. Merging H_i and H_j using the MOT2 algorithm will produce two new histories H_i and H_j that are identical. H designates the history resulting from the merge of H_i and H_j. The precedence between op_i and op_j in H is determined by the order between their generator sites. Property P2 expresses this result.

Property P2. Given op_i and op_j such that: $H_i = H_C.op_i.seq_i$ and $H_j = H_C.op_j.seq_j$, after merging H_i and H_j using MOT2, the precedence in the resulting history H is such that:

$$\text{if} \quad S_{op_i} < S_{op_j} \quad \text{then } op_i \rightarrow_H op_j$$

$$\text{if} \quad S_{op_i} > S_{op_j} \quad \text{then } op_j \rightarrow_H op_i .$$

Property P3 generalizes property P2 to the case of a sequence of operations.

Property P3. Given $op_i \in H_i$ and a sequence $seq \in H_j$, defined from the *same* state and such that $H_i = H_C.op_i.seq_i$ and $H_j = H_C.seq.seq_j$, after merging H_i and H_j using MOT2 the precedence in the resulting history H is such that:

$$\text{if} \quad \forall op \in seq: \quad S_{op} < S_{op_i} \quad \text{then} \quad seq \rightarrow_H op_i.$$

The proof is given in Appendix A2.

Given two operations op_k and op_l that occur consecutively in a history H produced by MOT2, the following theorem specifies that if they are concurrent then they are ordered according to their generator site.

Theorem 1. Given two operations op_k and op_l that occur consecutively in a history H produced by MOT2 and such that $op_k \rightarrow_H op_l$:

$$\text{if} \quad op_k \,//\, op_l \text{ then} \quad S_{op_k} < S_{op_l}.$$

The demonstration is given in Appendix A3. Theorem 2, obtained by contraposition, specifies that if the operations are both consecutive and ordered in the history according to the inverse order of their generator site, then they are related by a causal precedence relation.

Theorem 2. Given two operations op_k and op_l that occur consecutively in a history H produced by MOT2 and such that $op_k \rightarrow_H op_l$:

$$\text{if} \quad S_{op_k} \geq S_{op_l} \quad \text{then} \quad op_k \rightarrow_C op_l.$$

These theorems are illustrated by Example 6, when each sequence $h_i[n]$ corresponds to a single operation. The considered final history is:

$$\text{Synch } (S_2, S_1) \Rightarrow h_4[1].h_3[1].h_1[1].h_2[2].h_1[2].h_3[2].h_2[3].h_1[3].$$

We observe that consecutive concurrent operations ($h_4[1]$ and $h_3[1]$, $h_3[1]$ and $h_1[1]$, $h_2[2]$ and $h_1[2]$, $h_2[3]$ and $h_1[3]$) are actually ordered according to their generator site order (recall that in this example the site order is: $S_4 < S_3 < S_2 < S_1$). Concerning consecutive operations that are ordered according to the inverse order of their generator site ($h_1[1]$ and $h_2[2]$ on one hand, $h_1[2]$ and $h_3[2]$ on the other), they are actually related by a causal precedence relation: $h_1[1] \rightarrow_C h_2[2]$ and $h_1[2] \rightarrow_C h_3[2]$.

The following theorem is a generalization of Theorem 1. Its demonstration is given in Appendix A4.

Theorem 3. Given the sequence seq.op in a history H produced by MOT2, where seq is constituted from operations concurrent to operation op, then:

$$\forall op_k \in seq \quad \Rightarrow \quad S_{op_k} < S_{op}.$$

Theorem 4 is deduced by contraposition.

Theorem 4. Given the sequence seq.op in a history H produced by MOT2 where $seq = op_0....op_n$. If sequence seq contains an operation op_k such that $S_{op_k} \geq S_{op}$ then:

$$\exists\, op_l \in \{op_k....op_n\} \;\Rightarrow\; op_l \rightarrow_C op.$$

These theorems can be illustrated by the same example as given previously, still considering that each sequence $h_i[n]$ corresponds to a single operation. The final history considered is:

$$\text{Synch } (S_2, S_1) \Rightarrow h_4[1].h_3[1].h_1[1].\underline{h_2[2].h_1[2]}.h_3[2].h_2[3].h_1[3].$$

Let us consider the underlined sequence seq with op = $h_3[2]$; $h_2[2]$ (i.e. op_k) and $h_3[2]$ (i.e. op) are such that $S_2 > S_3$ (i.e. $S_{op_k} > S_{op}$), although $h_2[2]$ is concurrent to $h_3[2]$ (i.e. op_k // op); we actually observe that $h_1[2]$ (i.e. op_l) exists such that: $h_1[2] \rightarrow_C h_3[2]$ (i.e. $op_l \rightarrow_C op$).

Theorem 5 states that, when histories H_i and H_j produced by MOT2 contain common operations, then these appear in the *same* order.

Theorem 5. Given op_k and $op_l \in H_i$, op_k and $op_l \in H_j$, where H_i and H_j are histories produced by MOT2:

$$\text{if} \quad op_k \rightarrow_{H_i} op_l \quad \text{then} \quad op_k \rightarrow_{H_j} op_l .$$

The proof is given in Appendix A5. This theorem underlies the proof of the MOT2 algorithm. Indeed, as operations common to histories produced by MOT2 appear in the *same* order in these histories, we are sure that, whatever successive synchronizations occur, the histories which have integrated the same operations are *identical*. In other words, by means of synchronizations, histories associated with each copy integrate new operations and therefore converge towards the *same* history. So the MOT2 algorithm dynamically guarantees operation ordering according to a unique *global order* without requiring a centralising or ordering (timestamp, state vector, sequencer, etc.) mechanism.

Finally, the proof that the integration of an operation meets the validity conditions of SOCT4 (conditions (a) and (b) in section 2.5) is given in Appendix A6.

5. Conclusion

This paper has studied problems involving reconciliation of multiple divergent copies of the same object by means of a Synchronizer when using Operational Transformation. In this setting, we have proposed an original Synchronizer, i.e. MOT2, that enables the users to reconcile copies while ensuring their convergence and respecting the potential causal precedence between operations, without favouring any copy. MOT2 is particularly suitable for a P2P environment as it enables pairwise copy reconciliation, with any pair association, and without requiring a master site. Each site can thus synchronize its copy, *when it wants*, with *any* other site that owns a copy of the object. While permitting free propagation of update operations, MOT2 guarantees that they will appear in the *same order* in all the histories. It thus ensures, through successive synchronizations, the construction of a *global order* without requiring any ordering mechanism (timestamps, state vectors, sequencer). Finally, the Operational Transformation used (forward transposition only) necessitates verification of condition C1 only, which is easily met. The MOT2 algorithm can be centralized (it then runs on a single site) or distributed (it runs on two sites, each one owning a copy and the corresponding history). Here we have proposed a centralized version of the MOT2 algorithm in order to present its functioning principle and provide proof of its correction. It can be used as such in a distributed P2P environment by supplying each site with a version of MOT2. The algorithm is the *same* on all sites, with no site playing a specific role. Two sites only need to transmit their history to each other and then run MOT2 to achieve synchronization.

6. Appendix

A1. Proof of the MOT1 Algorithm

MOT1 is verified by checking that the integration of operations in each phase meets the SOCT4 validity conditions (conditions (a) and (b) of section 2.5). In phase (1), the operation op_k (with $op_k = H_R[k]$.operation) to be integrated at the same position k into H_S is such that: (a) it is defined from the state left by the $H_S[k-1]$.operation since $\forall j$: $1 \leq j \leq k-1$, $H_S[j] = H_R[j]$ and (b) $\forall j$: $k < j \leq \text{sizeof}H_S$, op = $H_S[j]$.operation is concurrent to op_k, because op has been generated at site S after the last synchronization of S with R. In phase (2), the operation op_k (with $op_k = H_S[k]$.operation) which is added to H_R at the same position k is such that: (a) it is defined from the state left by $H_R[k-1]$.operation since $\forall j$: $1 \leq j \leq k-1$, $H_R[j] = H_S[j]$ and (b) $\nexists$ op with op = $H_R[j]$.operation, $\forall j$: $k < j \leq \text{sizeof}H_R$ since $k = \text{sizeof}H_R$.

A2. Proof of Property P3

Let $H_i = H_C.op_i.seq_i$ and $H_j = H_C.seq.seq_j$ with $seq = op_1.op_2.....\ op_h$. As $S_{op_1} < S_{op_i}$, according to the P2 property, we have: $op_1 \rightarrow_H op_i$. As op_1 is integrated into the history H_i, after the first iteration of the algorithm we get: $H_i = H_C.op_1.op_i'.seq_i'$, where $op_i'.seq_i'$ is the forward transposition of $op_i.seq_i$ with op_1. If we only consider operation ordering, then $H_i = H_C.op_1.op_i.seq_i$. Now, let us consider $op_i \in H_i$ and $op_2 \in H_j$ which are defined on the same state (the one left by $H_C.op_1$). As $S_{op_2} < S_{op_i}$ according to P2 we get: $op_2 \rightarrow_H op_i$. After successive iterations, it turns out that $op_h \rightarrow_H op_i$. Finally, $op_1 \rightarrow_H op_2 \rightarrow_H ..... \rightarrow_H op_h \rightarrow_H op_i$ then $seq \rightarrow_H op_i$.

A3. Proof of Theorem 1

The operations op_k and op_l are concurrent, so we can deduce that they were joined together in the same history when synchronizing two sites. Let us call these sites S_i and S_j. Moreover, the operations op_k et op_l are consecutive. We can thus deduce that when histories H_i and H_j were merged, there was an integration step with: $H_i = H_C.op_k...$ and $H_j = H_C.op_l....$ Since the result of this step was $H_C.op_k.op_l...$, then, according to the P2 property: $S_{op_k} < S_{op_l}$. CQFD.

A4. Proof of Theorem 3

Operations of the sequence seq are concurrent to op, i.e. they were joined together in the same history as op as result of synchronizations. Let us consider the first synchronization when operation op and all or part of the sequence seq were joined together in the same history. Let us call this initial sequence seq_0. Let us denote S_i and S_j as the sites which got synchronized and let us assume that $op \in H_i$ and $seq_0 \in H_j$. Since seq_0 and op are consecutive in the resulting history, then there was, during some merging step: $H_i = H_C.op\ldots$ and $H_j = H_C.seq_0\ldots$. Since the result was $H_C.seq_0.op$, then, according to the P3 property: $\forall op_k \in seq_0$, $S_{op_k} < S_{op}$.

The sequence seq_0 increased with some further operations and finally became equal to seq as a result of the next synchronizations. If an operation op_l was added to seq_0, which constituted a new sequence denoted as seq_1, then, during some merge, operations op_l and op_m (with $op_m \in \{seq_0.op\}$) were defined on the same state and op_l was integrated *before* op_m (i.e. $op_l \rightarrow_H op_m$). More precisely, let us suppose that S_i and S_j are the sites which got synchronized and that $seq_0 = seq_x.op_m.seq_y$, then:

$$H_i = H_C.seq_x.op_m.seq_y.op\ ...$$

$$H_j = H_C.seq_x.op_l\ ...$$

Since the result of the merge was $op_l \rightarrow_H op_m$ then $S_{op_l} < S_{op_m}$. As $S_{op_m} < S_{op}$, after having integrated op_l into seq_0, we still have the property: $\forall op_k \in seq_1$, $S_{op_k} < S_{op}$. By repeating this reasoning for every operation added to seq_0, the property can finally be stated: $\forall op_k \in seq$, $S_{op_k} < S_{op}$. CQFD.

A5. Proof of Theorem 5

Two cases must be considered according whether operations op_k and op_l that belong to histories H_i and H_j are concurrent or not.

1) <u>op_k and op_l are not concurrent</u>

The operations were ordered according to the causality relation. One of the operations, let us say op_l, was generated at site S_{op_l} after execution of the other one at this site. In the history of S_{op_l}, according to definition 2, we can state: $op_k \rightarrow_C op_l$. As from the P1 property, merging preserves the precedence (and therefore the causal ordering precedence), *in all the histories* there will be: $op_k \rightarrow_C op_l$.

2) <u>op_k and op_l are concurrent</u>

The operations were generated independently of each other in distinct histories. As a result of synchronizing sites, operation op_k which was generated at site S_{op_k}, got propagated to other histories, denoted H^k. In the same way, operation op_l which was generated at site S_{op_l} got propagated to other histories, denoted H^l. Operations op_k and op_l are joined together in the same history when some site from H^l and some site from H^k get synchronized. We will demonstrate that *in any case* op_k and op_l will be ordered by MOT2 in the *same* way. There are again two situations according whether op_k and op_l were generated either from the same state or from different states of the copies.

2.1) <u>op_k and op_l were generated from the same copy state</u>

As op_k and op_l were generated from the *same* state, then: $\forall op_c$: $op_c \rightarrow_C op_k$ then $op_c \rightarrow_C op_l$

and conversely: $\forall op_c$: $op_c \rightarrow_C op_l$ then $op_c \rightarrow_C op_k$.

When synchronizing some site S_i from H^k and some site S_j from H^l, MOT2 execution will lead to one of the two following intermediate situations:

either (case 2.1.1): $H_i = H_C.op_k....$ and $H_j = H_C.seq.op_l....$

or (case 2.1.2): $H_i = H_C.seq.op_k....$ and $H_j = H_C.op_l....$

Since $\forall op_c$: $op_c \rightarrow_C op_k$ then $op_c \rightarrow_C op_l$ and conversely: $\forall op_c$: $op_c \rightarrow_C op_l$ then $op_c \rightarrow_C op_k$, in both cases we get: $\forall op_c$: $op_c \rightarrow_C op_k$ <u>or</u> $op_c \rightarrow_C op_l$, $op_c \in H_C$. Then: $\forall op \in seq$: op // op_k and op // op_l.. Hereafter, we have to show that, in both cases, synchronization will produce the same result. Let us suppose that $S_{op_k} < S_{op_l}$ (the same reasoning holds for $S_{op_k} > S_{op_l}$).

In case 2.1.1, according to the P2 property, in the resulting history H, we necessarily get: $op_k \rightarrow_H op_l$.

In case 2.1.2, according to the theorem 3, we get: $\forall op \in seq$, $S_{op} < S_{op_k}$. Based on $S_{op_k} < S_{op_l}$ and taking property P3 into account, in the resulting history H, we necessarily get: $seq \rightarrow_H op_k \rightarrow_H op_l$.

Finally, we obtain the following result.

Two concurrent operations op_k and op_l, which were generated from the *same* copy state, are ordered in the resulting history according to their generator site:

if $S_{op_k} < S_{op_l}$ then $op_k \rightarrow_H op_l$

if $S_{op_l} < S_{op_k}$ then $op_l \rightarrow_H op_k$

Therefore, they are ordered in the same way in all the histories.

2.2) <u>op_k and op_l were generated from different copy states</u>

In this case, op_k and op_l are said to be *partially concurrent.* This means there is an operation op_m such that:

either: $op_m \rightarrow_C op_l$ and op_m and op_k were generated from the same state,

or: $op_m \rightarrow_C op_k$ and op_m and op_l were generated from the same state.

Let us consider the first case (similar reasoning is required for the second one). Since op_m and op_k are concurrent and were generated from the same state, according to the framed result obtained in 2.1, they will be ordered in the resulting history according to their generator site. Two cases thus have to be investigated depending on the respective values of S_{op_k} and S_{op_m}.

2.2.1 <u>Case where $S_{op_k} < S_{op_m}$</u>

In this case, we get: $op_k \rightarrow_H op_m$. By hypothesis, we also have $op_m \rightarrow_C op_l$. As any history containing op_l also contains all operations which causally precede op_l, we deduce that any history of H^l contains op_m. Consequently, when synchronizing any site of H^l with any site of H^k, in the resulting history we get: $op_k \rightarrow_H op_m \rightarrow_C op_l$ and therefore $op_k \rightarrow_H op_l$.

Finally, by applying a similar reasoning to the second case, we obtain the following result.

Two partially concurrent operations op_k and op_l (i.e. which were generated from different states) are ordered in the resulting history in the following way:

if $\exists\, op_m$: $op_m \rightarrow_C op_l$ and op_m and op_k were generated from the same state

and if $S_{op_k} < S_{op_m}$ then $op_k \rightarrow_H op_l$;

if $\exists\, op_m$: $op_m \rightarrow_C op_k$ and op_m and op_l were generated from the same state

and if $S_{op_l} < S_{op_m}$ then $op_l \rightarrow_H op_k$.

As any history containing an operation also contains all operations which causally precede it, we deduce that any history containing op_l [resp. op_k] also contains op_m. Therefore, op_k and op_l are ordered in the same way in all histories.

2.2.2 Case where $S_{op_k} > S_{op_m}$

In this case, we get in the resulting history: $op_m \rightarrow_H op_k$. More precisely, execution of the MOT2 algorithm will produce the intermediate result:

firstly, $H_i = H_C.op_k....$ and $H_j = H_C.op_m....op_l....$

then, $H_i = H_C.op_m.op_k....$ and $H_j = H_C.op_m....op_l....$ where op_k has been forward transposed with op_m

The op_k operation obtained after being forward transposed is defined from the state $H_C.op_m$, as if it had been generated from this state. Hereafter, the problem is to determine the respective positions of this new operation op_k and op_l. We are then led again to the beginning of case 2. The reasoning is iterated until obtaining a relation between op_k and op_l relevant to case 2.1 or case 2.2.1. CQFD.

The characterisation of two operations to be concurrent and generated from the same state, or partially concurrent, changes with the algorithm execution. Two operations which are initially partially concurrent, may later become concurrent by the effect of successive transpositions.

A6. Proof of the Correct Integration of an Operation in MOT2

We have to prove that the integration of an operation meets the validity conditions of SOCT4 (conditions (a) and (b) of section 2.5).

During execution of MOT2, when two sites S_i and S_j are synchronized, the integration procedure is called to integrate an operation op of H_i into H_j under the following circumstances: $H_i = H_C.op.seq_i$, $H_j = H_C.op_k.seq_j$ and $S_{op} < S_{op_k}$; op is then integrated into H_j after H_C and before op_k.

Condition (a) is verified since op is defined from the state produced by H_C.

In order to verify condition (b), we must show that:

$$\forall\, op_l \in op_k.seq_j,\ op_l \,//\, op \text{ (i.e. } \underline{\text{not}}\ (op \rightarrow_C op_l)\ \underline{\text{and}}\ \underline{\text{not}}\ (op_l \rightarrow_C op)).$$

1. Let us suppose that: $\exists\, op_l \in op_k.seq_j$ such that $op \rightarrow_C op_l$. It turns out that op also belongs to H_j and then we get more precisely: $H_j = H_C.op_k.seq_{j_1}.op.seq_{j_2}.op_l.seq_{j_3}$. We deduce that: $\forall\, op_m \in op_k.seq_{j_1}$, op_m is concurrent to op, and therefore according to theorem 3, $\forall\, op_m \in op_k.seq_{j_1}$, $S_{op_m} < S_{op}$. Here there is a contradiction with the hypothesis $S_{op} < S_{op_k}$.

2. Let us consider an operation op_m such that: $op_m \rightarrow_C op$. Since any operation which causally precedes op belongs to H_C, op_m belongs to H_C and therefore: $\forall\, op_l \in op_k.seq_j$, <u>not</u> $(op_l \rightarrow_C op)$. CQFD.

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